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Comparison of cage designs for transforaminal lumbar interbody fusion: A biomechanical study

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Abstract

Background. Prior biomechanical studies of transforaminal lumbar interbody fusion were primarily focused on various posterior instrumentation options, comparison with other fusion techniques, and cage positioning inside disc space. Few studies investigated the biomechanics of various cage designs in terms of construct stability.

Methods. Twelve lumbar motion segments were used in this study. The experimental procedure has two steps: multidirectional flexibility test and cyclic test. In the multidirectional flexibility test, all twelve specimens were tested following intact and five different cages (straight or banana shaped). The straight cages had biconvex or flat profile. In the cyclic test, the twelve specimens were randomly divided into two groups for biconvex and flat cages. Three thousand cycles in axial torsion, lateral bending and flexion extension were applied sequentially and cage migration was measured.

Findings. On average, the cage and posterior fixation reduced the range of motion of the intact condition by 40%, 69% and 75% in axial torsion, lateral bending and flexion extension, respectively. There was no statistical difference in construct stability among all five cages. The cage migration (biconvex vs flat) under cyclic loading was less than 0.2 mm and no statistical difference was found.

Interpretation. The experimental results suggest that the geometry of cages, including shape (banana or straight), length, and surface profile (biconvex or flat), does not affect construct stability when the cages are used in conjunction with posterior fixation. With posterior fixation and surface serration, cage migration was minimal under cyclic loading for both biconvex and flat cages.

1. Introduction

Transforaminal lumbar interbody fusion (TLIF) is a popular technique for treating chronic low back pain. The safety and efficacy of this technique have been demonstrated in many clinical studies (Rosenberg and Mummaneni, 2001; Salehi et al., 2004; Lowe et al., 2002; Potter et al., 2005; Holly et al., 2006). Compared with other fusion techniques, TLIF offers many advantages, such as small incision, low blood loss and short hospital stay (Hee et al., 2001). Compared with posterior lumbar interbody fusion (PLIF), TLIF requires less nerve root retraction and can reduce complication rate (Humphreys et al., 2001). TLIF can be performed with open approach, mini-open or minimally invasive approach according to a patient's specific needs.

A critical component of the fusion process is the interbody spacer or cage. The fusion cages are designed to restore normal disc height, improve construct stiffness and thus reduce posterior instrumentation failure. The TLIF cages can share significant amount of load even with the posterior fixation (Polly et al., 2000). Due to the load bearing nature of TLIF cages, the material choice, positioning inside the disc space and shape of TLIF cages can affect the biomechanics of the construct and lead to various clinical results. Various materials, including titanium, femoral cortical allograft, and polyetheretherketone (PEEK, sometimes reinforced with carbon fibers), have been used for fabricating TLIF cages (Spruit et al., 2005;

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Cutler et al., 2006). PEEK is the favored choice because of its unlimited supply, its close match to the stiffness of vertebral bones and its radiolucent property (Ferguson et al., 2006; Vadapalli et al., 2006b; Cutler et al., 2006). The positioning of cages appears to cause different effect in load sharing on synthetic and finite element models (Polly et al., 2000; Cheng, 2002 #50). However, in vitro studies on human cadaveric lumbar segments showed no statistical difference in construct stability when the cage was placed either in the anterior or posterior position (Ames et al., 2005).

Different cage designs have been used in TLIF procedures to simplify surgical implantation and improve biomechanical performance. For example, the bullet shaped nose of TLIF cages (Stryker AVS TL and AVS PL) is intended to achieve easy insertion and safe navigation around neural tissues. The biconvex cage (Medtronic Capstone) is designed to better fit the concave shape of the superior and inferior endplates. Serrated surfaces of a TLIF cage can be used to lock the cage's position to avoid migration. Prior biomechanical studies of TLIF were primarily focused on various posterior instrumentation options (Harris et al., 2004), comparison with other fusion techniques (Ames et al., 2005; Niemeyer et al., 2006), and cage positioning inside disc space (Ames et al., 2005). Although many studies characterized the compressive strength of different cage designs (Jost et al., 1998; Krammer et al., 2001; Lowe et al., 2004), few studies investigated the biomechanics of various cage designs (Lund et al., 1998; Groth et al., 2005; Vadapalli et al., 2006a) in terms of construct stability, especially the ones that are widely used today. The purpose of this study is to compare three popular TLIF implant designs (Stryker AVS PL, AVS TL and the Medtronic Capstone) with different lengths and shapes (flat or biconvex, straight or banana shape) in terms of biomechanical stability on human cadaveric models. It is hypothesized that a longer cage and flat cage may provide better stability. In addition, potential cage migration due to cyclic loading was also evaluated to assess the risk of cage expulsion.

2. Methods

Twelve lumbar motion segments, harvested from eight human cadavers, were used in the study. Each motion segment had two lumbar vertebrae. Four donors were male and four were female. The mean age was 62 years (ranged from 48 to 75). All specimens were screened via fluoroscopy in order to identify any major anatomical abnormality (e.g. fracture, dysplasia). To ensure that each specimen had consistent and adequate bone quality, dual energy X-ray absorbtiometry (Lunar Prodigy, GE, Louisville, KY, USA) was performed in anterior posterior direction to measure the bone mineral density of each vertebra. The average T score was −1.4. All specimens were stored at −20° C until the day of testing, and were allowed to thaw slowly at room temperature. Six wood screws (two of which were attached to the facet joints) were driven into the cephalad or caudad side of each intact specimen. Once the anchoring screws were inserted, the specimen was potted in polyurethane casting resin (R1 FastCast, Goldenwest MFG, Cedar Ridge, CA, USA) with the upper or lower endplate parallel to the potting cup base.

All specimens were tested in two steps. The first step is the multidirectional flexibility testing of various surgical treatments including intact condition. This step determined the immediate construct stability using five different cages: AVS TL (25 mm), AVS PL (25 mm), AVS PL (20 mm), Capstone 26 mm and Capstone 32 mm. Fig. 1 shows these three types of cages. The AVS TL has a banana shape where as the AVS PL has a shape with flat superior and inferior surfaces. The Capstone cage is also straight but has biconvex superior and inferior surfaces. The straight cages can be inserted into the disc space in an oblique angle and are sometimes referred to as PLIF cages. The height of the cages was selected according to the disc height of each individual specimen. All cages were tested with posterior fixation (Stryker Xia polyaxial screws with 6.5 mm in diameter and 45 mm in length and rods with 5.5 mm in diameter). The AVS cages were manufactured by Stryker Spine, Allendale, NJ, USA and Capstone cages were manufactured by Medtronic, Memphis, TN, USA. Because the present study is comparative, all surgical treatments were repeated on the same specimen. However, the order of each treatment was randomized to reduce the effect of fatigue and specimen degradation due to repeated loading.

The second step was cyclic testing and involved repeated loading to determine the cage migration of two different designs: biconvex or flat PLIF cages. In this step, the twelve specimens were divided into two groups for the following two types of cages: AVS PL (25 mm parallel) and Capstone

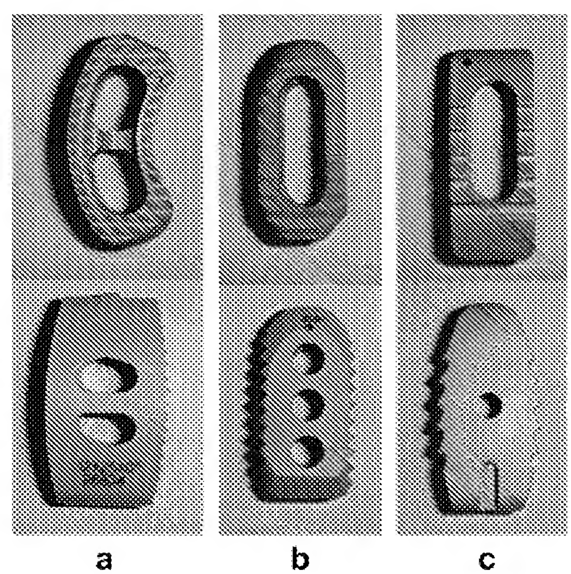

Fig. 1. Three types of TLIF cages were evaluated for their biomechanics including (a) banana shape (b) flat and straight shape (c) biconvex and straight shape.

(26 mm biconvex). The same posterior fixation was applied in the cyclic test.

In the multidirectional flexibility test, unconstrained and nondestructive pure moments in axial torsion, lateral bending and flexion extension were applied to each specimen under 0.05 Hz and ±7.5 Nm sinusoidal waveform with an MTS Bionix 858II spine simulator (MTS, Eden Prairie, MN). The spine simulator consisted of an axial torsion actuator and two rotational actuators for lateral bending and flexion extension. These actuators were mounted on the upper side of the test machine. A low friction cross roller slide table mounted on the lower side allowed pure bending moments to be applied to the specimen. Three cycles were applied for each loading condition with the last cycle used for data analysis. A 150 N axial compression load was maintained throughout each test. Because of the absence of muscle and joint support, a small axial compression load was applied not to damage the specimen. Segmental motion was recorded at 10 Hz with an OptoTrak Certus video tracking system (NDI, Ontario, Canada). The video tracking system had 0.1 mm of spatial accuracy for each optical diode. Two rigid bodies consisting of four optical diodes each were attached to the two vertebrae in each specimen. The range of motion was calculated based on marker position data recorded with the video tracking system. Our pilot experiments showed that this configuration was able to achieve 0.1 degree of accuracy in rotation angle.

After the multidirectional flexibility test was completed, the cyclic test was conducted on the same specimen to characterize the effect of cage designs on implant migration after repeated loading. The cyclic moment in each load condition (axial torsion, lateral bending and flexion extension) was applied continuously for 3000 cycles at 0.2 Hz and 85 Nm sinusoidal waveform. A total of 9000 cycles were applied to induce potential cage migration. The magnitude of the cyclic load was reduced to ±5 Nm to prevent loosening of the anchoring screws, which fixed the vertebrae to the potting material. The cyclic test did not record the range of motion as a function of cycles. Instead, the cage location after cyclic loading was measured using plain radiographs. The two potting bases of each specimen were marked such that X-rays can be taken with consistent position. Radiographic markings on the cage were used as a reference to calculate the relative migration. Fig. 2a and b illustrates the measurement technique for the cage migration after cyclic loading. The precision of this technique was found to be 0.2 mm on our pilot experiments.

The cage migration was measured in both lateral and anterior posterior direction with plain radiographs. Fig. 2a shows the cage position in the lateral direction before the cyclic test. A bony landmark was selected on the inferior posterior corner of the upper vertebra. The white line was drawn to measure the distance between the radiographic marking of the cage and the bony landmark. After cyclic loading, the cage position was measured in the same direction with plain radiographs. Fig. 2b shows the white line drawn in the same manner as it was before the cyclic test. The difference between the white line's lengths measured before and after the cyclic test was defined as the cage migration. Finally, all specimens were dissected and their endplates were inspected for any sign of cage subsidence.

The TLIF procedure began with a unilateral facetectomy on either side of the spine. The choice of the side was randomized to avoid any potential effect of sidedness. Once the inferior and superior facets were removed with an osteotome, decortication was carefully performed for pedicle screw placement. Pilot holes were created with a tapered probe. Afterwards, the pedicle screws were driven

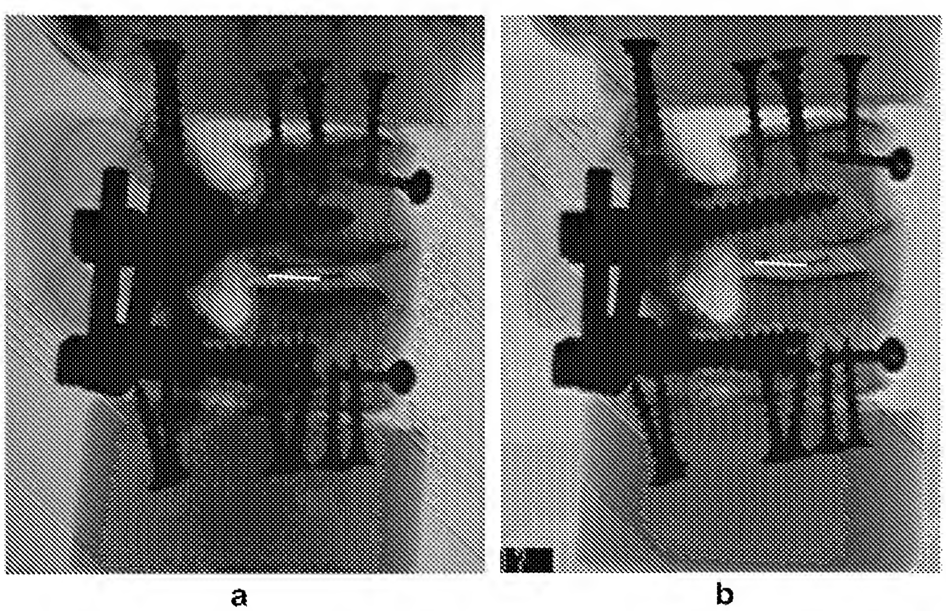

Fig. 2. Cage migration measured in the lateral position (a) distance measured before cyclic loading and (b) distance measured after cyclic test.

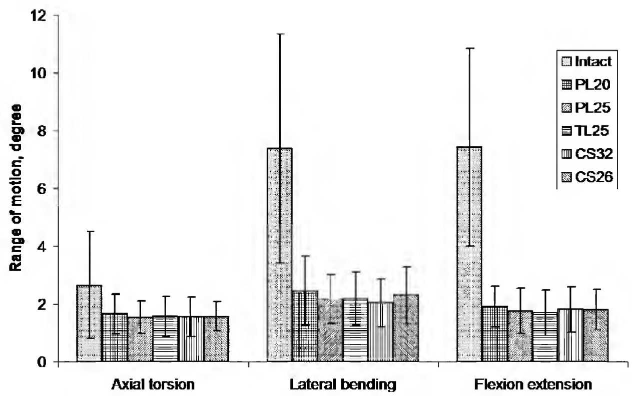

Fig. 3. Mean range of motion of all five cages ($n = 12$). Error bars represent standard deviation. PL20 and PL25 are AVS PL 20 mm and 25 mm cages, respectively. TL25 is AVS TL 25 mm cage. CS26 and CS32 are Capstone 26 mm and 32 mm cages, respectively.

into the vertebral body. Once the foraminal site was prepared, the spinous process was distracted with a spreader to expose the posterolateral annulus. A posterolateral annulotomy was then performed followed by a discectomy with curettes and pituitary rongeurs. The disc space was prepared properly before trials were used to determine the spacer height. The height of the cages was determined to ensure a tight fit. Each TLIF cage was tapped firmly into the distracted disc space with a mallet. For consistency, the AVS TL cages were placed on the anterior side and as symmetrically as possible along the sagittal plane. The AVS PL and Capstone cages were inserted at an oblique angle. Finally, two straight titanium rods (5.5 mm) were securely attached to the pedicle screws with a torque wrench and a compressor. The compression force was applied as consistent as possible. Once the surgical procedure for the first cage (one of the five cages listed previously) was completed, the positioning of cages and pedicle screws was verified using plain radiographs. Afterwards, the multidirectional flexibility test was performed on the instrumented specimen. When the test was finished, the specimen was removed from the test machine and the spinal rods were loosened to remove the cage. The next cage was inserted, and the pedicle screws were retightened with appropriate compression. The test was repeated until all five cages had been tested. The surgical procedure for the cyclic test was the same as that for the multidirectional test (see Fig. 3).

3. Data analysis

The neutral zone data of all instrumented specimen were less than 0.5° and are not reported here. In multidirectional flexibility testing, there were a total of twelve specimens. The range of motion of the intact and five TLIF cages was analyzed using repeated measures one way ANOVA. Post hoc comparisons among different cages were performed using Newman–Keuls tests. The AVS TL and AVS PL cages (same length) were compared to show the difference between banana and straight cage designs. The AVS PL and Capstone cages (25 mm and 26 mm, respectively) were compared to show the difference between biconvex and flat designs in the straight cages. Finally, two lengths in AVS PL (25 mm vs 20 mm) and Capstone (26 mm vs 32 mm) were compared to study the effect of cage length.

For the cyclic test, there were two independent groups (AVS PL 25 mm and Capstone 26 mm). The measured migration in mm of the two groups was compared with Mann–Whitney non parametric test.

4. Results

After the cyclic test, there was no sign of cage subsidence for both AVS PL and Capstone cages on plain radiographs. Dissection of the fusion site confirmed that both endplates were intact after the cyclic loading. The results of the multidirectional flexibility testing of all 12 lumbar motion segments are summarized in Fig. 1. The mean range of motion under intact condition was 2.65° (SD 1.85°), 7.37° (SD 3.97°) and 7.42° (SD 3.41°) in axial torsion, lateral bending and flexion extension, respectively. With posterior fixation, all cages reduced range of motion significantly ($P < 0.001$). On average, the TLIF cages and posterior fixation reduced the range of motion of the intact state by 40%, 69% and 75% in axial torsion, lateral bending and flexion extension, respectively. There was no statistical difference among all five cages in measured range of motion.

The migration of two cages (PL25 and CS26) under cyclic loading was nearly zero. The average migration for both cages was less than 0.2 mm. There was no statistical difference between these two cages in both lateral and anterior posterior direction ($P = 0.8$).

5. Discussion

In addition to the variety in material choices, a number of structural designs of lumbar fusion cages have been developed. In general, these designs include threaded cylindrical cages, titanium mesh cages, wedged structural allograft, banana shaped cages and bullet shaped cages. Despite promising biomechanical results in a number of in vitro studies (Groth et al., 2005; Kettler et al., 2005; Lund et al., 1998), the threaded BAK cages have higher rate of complications, such as implant subsidence and cage migration (Beutler and Peppelman, 2003; Chen et al., 2005). Recently, the majority of commercially available TLIF cages, such as AVS (Stryker Spine), Verte-stack Capstone and Crescent (Medtronic), Lumbar I/F and Leopard (Depuy Acromed), and TraXis (Spinal Concepts), have either banana shape or straight shape. These cages are often made from PEEK. The banana shaped cages are preferably placed in the anterior side of disc space. The other popular type of TLIF cages is the straight design, sometimes also referred to as PLIF cages. These straight

shaped cages are easier to position than the banana shaped cages. Our experimental results suggested that the banana shaped (AVS TL) and straight bullet shaped (AVS PL) cages had similar construct stability when they were utilized in conjunction with additional posterior fixation. This is consistent with the results reported by Ames (Ames et al., 2005).

Other than the shape of TLIF cages, the width of TLIF cages also does not affect construct stability when posterior fixation is applied (Vadapalli et al., 2006a). Furthermore, the present study suggests that the length of cages does not affect construct stability. Although standalone TLIF cages appear to have different biomechanics when different cages are used (Kettler et al., 2005), the experimental results of the present study suggest that the geometry of cages does not affect construct stability when posterior fixation is applied. All five different cages (shape, contact surface (biconvex or flat), and length) had similar construct stability when they were used in conjunction with posterior fixation. This result is probably caused by the fact that the pedicle screw and rod system provides very strong fixation. Thus, the load being transferred through the anterior column is significantly reduced. As long as there is reasonable amount of contact area in the anterior column, the construct stability appears to be adequate. Furthermore, there was no cage subsidence after cyclic loading for both flat and biconvex PLIF cages with posterior fixation. This result is consistent with clinical results because cage subsidence is not common when pedicle screw and rod system is used.

With posterior fixation, all TLIF cages in this study achieved significant stabilizing effect compared with the intact condition. Although one biomechanical study showed that TLIF with posterior fixation could only achieve similar stability to that of the intact condition (Harris et al., 2004), more studies suggested that TLIF could significantly improve biomechanical stability (Ames et al., 2005; Lund et al., 1998; Niemeyer et al., 2006; Vadapalli et al., 2006a). The present study also showed that regardless of the geometry of cages, the TLIF technique could effectively stabilize an intact spine in all loading directions.

The top and bottom surfaces of the straight PLIF cages can be biconvex (Capstone) or flat (AVS PL). An intact spinal motion segment has concave endplates and has rocking motion (McCulloch and Transfeldt, 1997) in flexion extension. A biconvex cage might fit in the disc space better, but might also act as rotation center and lead to decreased construct stability. The experimental results in the present study indicate that the biconvex and flat PLIF cages have similar construct stability. This is due in part to the fact that the posterior fixation reduces motion and shifts the center of rotation posteriorly in flexion extension. The rocking motion seen in an intact spine is no longer present in motion segments augmented with posterior instrumentation.

There is also a concern for cage migration under cyclic loading because of the risk of implant dislodgement in clinical applications. To simulate physiological conditions, the specimens were subjected to cyclic loading in axial torsion, lateral bending and flexion. Both the biconvex and flat cages had nearly zero cage migration. This result can be attributed to the serrated surfaces of all TLIF cages and small segmental motion due to posterior fixation. Furthermore, the compression force applied during screw tightening also helped stabilize cage position inside the disc space. Serrated surfaces are designed to eliminate cage migration instead of providing fixation. There are significant differences in the number of serrations between the Capstone and AVS implants. Regardless of length (22mm, 26mm or 32mm), the Capstone implants have a consistent 10 serrations or fixation points on the superior and inferior surfaces. The AVS implant, on the other hand, has serrations or fixation points which span the entire implant, independent of length. However, the clinical relevance of these results is unknown, especially with varying patient anatomies, degrees of degeneration, patient age, bone quality and operative level, which will directly affect the ability to optimally position any implant.

All tests on each specimen took approximately one day (24 h). In this study, we wrapped moistened gauze around each specimen during cyclic loading. There were signs of mild degradation, such as discoloration and smell after 24 h. It has been shown that within 20 h, the increase in range of motion on intact motion segments is approximately 10% (Wilke et al., 1998). In this study, because all specimens were stabilized with cage and posterior fixation, the biomechanical change is expected to be smaller assuming that soft tissues are often more sensitive to degradation than bones. No pedicle screw loosening was observed after all tests were completed. Furthermore, the purpose of the cyclic loading is to quantify cage migration rather than construct stability. Thus, the degradation effect due to extended exposure to room temperature is relatively small.

The limitation of the study is that the local stresses at the cage endplate interface were not considered. It must be recognized that different cage geometry may lead to different local stresses at the endplates. Many studies have shown the importance of cage size and contact area in avoiding cage subsidence (Jost et al., 1998; Krammer et al., 2001; Tan et al., 2005). It is believed that a bigger sized cage tends to have a bigger contact surface area at the cage endplate interface and thus lower local stress concentration. In patients with osteoporosis, enough cage endplate contact surface area should be maintained to avoid subsidence. In patients with degenerated discs, the endplates might be flattened. In this case, a flat surface cage, such as AVS PL is desired to increase contact surface area and avoid subsidence. The biconvex cage tends to concentrate the load and engages only the central portion of the endplate, which is the weakest region of the endplate (Lowe et al., 2004). Thus, the risk of cage subsidence is higher, especially for patents with poor bone quality. On the other hand, it must also be recognized that the bone growth is affected to some extent by the compression stresses at the cage end-

plate interface. Excessive contact surface area reduces the compression stress and is not necessarily beneficial for bone growth. Each patient must be carefully evaluated to determine the optimal cage size and geometry.

6. Conclusions

This study evaluated the biomechanics of various TLIF cages in terms of construct stability on human cadaveric models. The tested cages include banana shaped and straight cages. The straight cages had different lengths and had either biconvex or flat serrated top and bottom surfaces. In addition, cyclic loading was applied to the biconvex and flat straight cages (similar length) to measure cage migration. The experimental results showed that the geometry of cages, including shape (banana or straight), length, surface profile (biconvex or flat), did not affect construct stability when the cages were used in conjunction with posterior fixation. Cage migration was minimal under cyclic loading for both biconvex and flat cages.

Conflict of interest statement

No conflict of interest with other commercial party. No benefits in any form have been received or will be received from a commercial party related to the subject of this article.

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